Stationary Potential Jumps in a Plasma

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In a current-carrying plasma with $v_d < v_{Te}$ the existence of localized stationary potential jumps with $e\varphi/kT_e > 1$ is demonstrated. High-frequency ($\approx f_{pe}$) noise and low-frequency ($<f_{pi}$) noise with $W/nT_e \approx 0.2$ peak around the transition region. Ion and electron heating is observed. High anomalous resistivity is found on the high-potential side of the jump, with a maximum value within the jump.

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In recent years it has been shown theoretically[1-4] and experimentally[5-8] that large potential gradients can exist in the plasma. It is known that the Buneman and Pierce instability induce the formation of potential jumps in an electron-beam–plasma system.[8] Up to the present, from both theoretical and experimental results,[6,7] it was believed that a necessary condition for the formation of potential jumps was that the electron drift velocity v_d exceed the electron thermal velocity v_{Te}.

In this Letter, we present for the first time experimental evidence for the existence of a stationary potential jump with $e\varphi/kT_e \approx 5$ in a current-carrying plasma in which the electron drift velocity v_d is only $0.2v_{Te}$ $[v_{Te} = (8kT_e/\pi m)^{1/2}]$.

The experiment was performed in a long cylindrical triple plasma device. The length and diameter of the stainless steel central section are 300 and 20 cm, respectively. The end sections are 30 cm long and contain electron-emitting filaments to produce an argon plasma ($p = 4\times 10^{-4}$ Torr). The filaments inside the end sections are heated to produce equal electron emission currents. The plasma drifts into the grounded central section through grids, guided by a magnetic field of 25 G. A current can be established in the plasma by biasing one of the sources and its grid (Fig. 1). In the absence of a current, typical operating parameters are $n_e \approx 2\times 10^9$ cm^{-3}, $T_e \approx 1.2$ eV, and $T_i \approx 0.2$ eV.

The basic plasma parameters, such as the electron density, the electron temperature, and the low-frequency fluctuations δn, were monitored by a small cylindrical Langmuir probe (diameter $= 0.3$ mm). A movable probe consisting of two plane Langmuir probes facing opposite directions was used to measure the electron drift velocity on axis, along the central section. The normalized drift velocity v_d/v_{Te} was obtained from the difference between the electron saturation currents of the two plane probes. The same probe was used to measure the upstream and downstream electron distribution functions $f_e(v)$. The upstream and downstream ion temperatures were measured by a movable ion-energy analyzer with an energy resolution of 0.1 eV. The local plasma potential along the axis was monitored by a small emissive probe. The low- ($<f_{pi}$) and high- ($\approx f_{pe}$) frequency spectra were recorded by a capacitive probe which is known[9,10] to have a flat frequency response up to frequencies around f_{pe} (≈ 400–500 MHz). A Langmuir probe would draw a dc current which makes the recorded spectra meaningless.[11] A capacitive probe, however, does not suffer from this drawback.

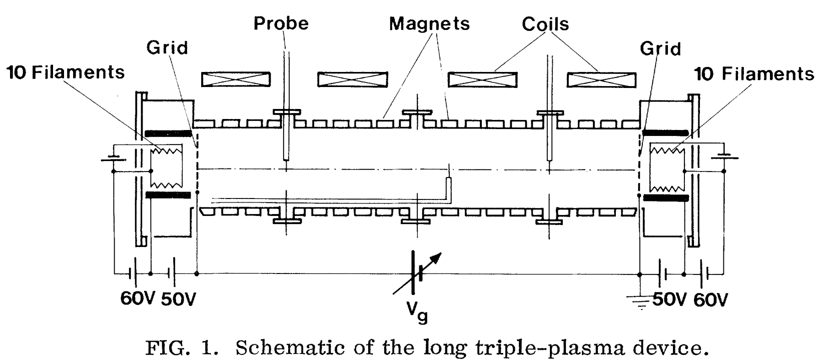

FIG. 1. Schematic of the long triple-plasma device.

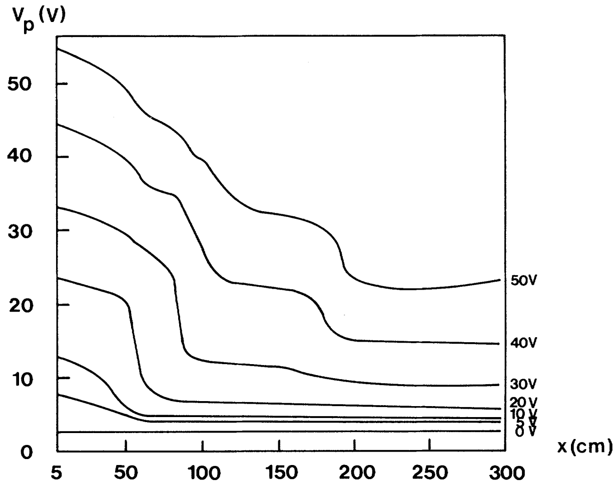

FIG. 2. Steady-state plasma potential vs position as a function of the grid bias V_g. The biased grid is located at the position $x = 0$.

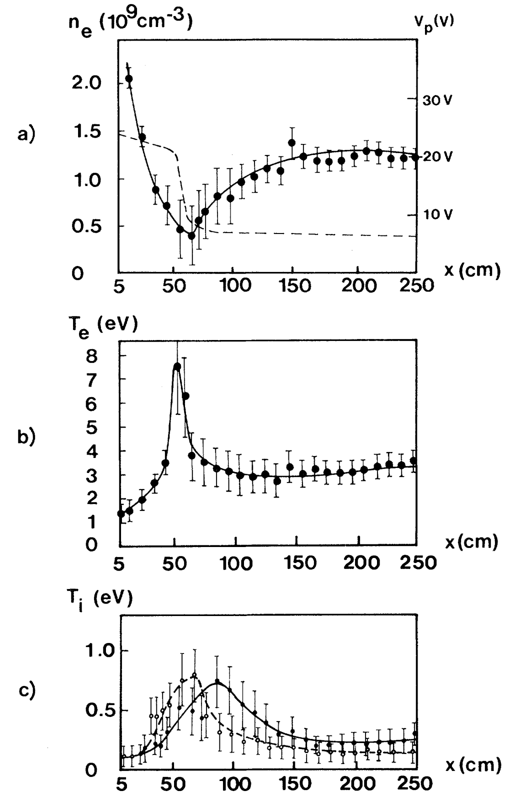

FIG. 3. (a) Electron density vs position for $V_g = 20$ V. (Dotted line: plasma potential profile.) (b) Electron temperature vs position for $V_g = 20$ V. (c) Ion temperature vs position for $V_g = 20$ V. (Open circles, upstream; closed circles, downstream.)

The plasma potential along the central section is shown in Fig. 2 as a function of the biasing voltage V_g. The formation of potential jumps is observed for grid voltages higher than about 5 V. For voltages higher than 30 V even two or three jumps are created. The heights of the potential jumps are of the order of $e\varphi/kT_e \approx 5$ and their width is typically 300–500 Debye lengths.

A more detailed study has been made for $V_g = 20$ V. The electron-density profile shows a pronounced depression at the center of the jump [Fig. 3(a)]. Furthermore, an increase in the electron and ion temperature has been observed [Figs. 3(b) and 3(c)]. For frequencies below ω_{pi} the normalized turbulent wave energy $(\delta n/n)^2 \cong W/nT_e$ varies between 10^{-3} and 0.2 [Fig. 4(a)]. The fluctuation level always peaks at the low potential foot of the potential jump. The frequency spectra show that most of the turbulent wave energy is concentrated below $f_{pi}/2$ [Fig. 4(a)]. For high W/nT_e, we observe an increase in the fluctuations at frequencies below 20 kHz. All the measured spectra indicate that there is no simple dependence on ω such as that proposed by Kadomtsev.[12]

An electron beam has been detected, located near the jump, on the high-potential side. It is found that the measured beam energy agrees with the energy the electrons could gain as they cross the potential step. High-frequency fluctuations have been observed in that region [Fig. 4(b)]. The spectrum is centered around f_{pe} and has a full width of about $0.3f_{pe}$. A localized increase of the electron temperature ($\Delta T_e \approx 3$–4 eV) in that region can be attributed to the thermalization of the electron beam. The measured value for the electron drift velocity remains of the order of $0.2v_{Te}$ [Fig. 5(a)]. Anomalous resistivity has been observed [Fig. 5(b)]. On the high-potential side of the jumps, the effective collision frequency has been found to be about 100 times the classical value. Only 10 times the classical value has been observed on the low-potential side of the jump. However, a value up to $700\nu_{cl}$ prevails within the jump. At this location, the effective mean free path ($\lambda = 1 \approx 2$ cm) has been found to be much smaller than the width of the observed jump ($L = 10$–15 cm). Thus the region within the jump is dominated by turbulent collisions.

The interpretation of these measurements is not easy. We do not know of any theory which would explain in a consistent manner all of our observations.

Several theories can be excluded. Laminar

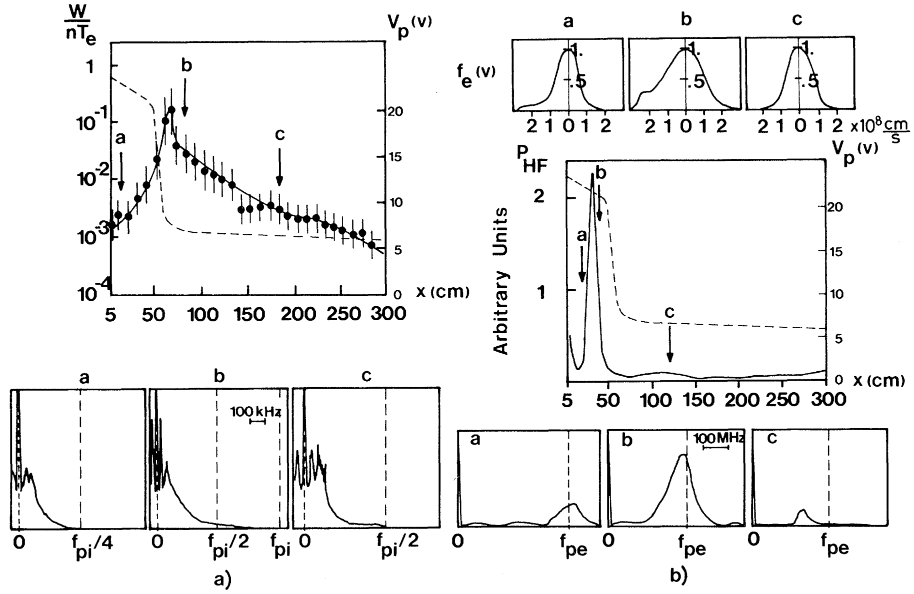

FIG. 4. (a) Normalized turbulent wave energy W/nT_e for frequencies below the ion plasma frequency as a function of position for V_g = 20 V. (Dotted line: corresponding potential profile.) Power spectra (linear scale) as measured by the capacitive probe at three different positions from the biased grid. (b) High frequency noise for frequencies below the electron plasma frequency vs position with power spectra (linear scale) measured by the capacitive probe at three different positions from the biased grid, for V_g = 20 V. (Dotted line: corresponding potential profile.) Electron distribution functions $f_e(v)$ for the same three locations along the central section of the device.

double layer theory is certainly not applicable in such a highly turbulent plasma. The observed frequency spectrum does not resemble the one derived by Kadomtsev (Ref. 12). Formulas of type $\nu^* = \alpha\omega_{pe} W/nT_e$,[13] where ν^* is the effective collision frequency, do not represent the observed facts [Fig.

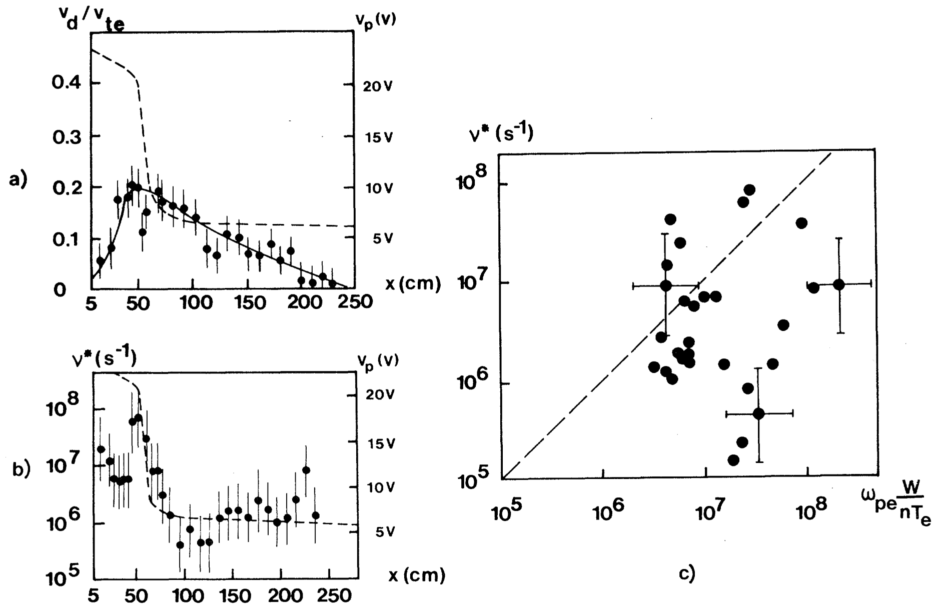

FIG. 5. (a) Normalized electron drift velocity v_d/v_{T_e} [$v_{Te} = (8kT/\pi m_e)^{1/2}$] vs position for V_g = 20 V. (Dotted line corresponding to plasma potential profile.) (b) Effective collision frequency ν^* vs position. (c) Effective collision frequency ν^* vs $\omega_{pe}(W/nT_e)$. Dotted line: corresponding to the scaling law $\nu^* = \omega_{pe} W/nT_e$.

5(c)]. However, some features of this turbulence are compatible with the following interpretation.

The electron beam seen on the top of the step has the energy of the step suggesting that it is the step which accelerates these electrons. Langmuir noise appears on the high side of the step together with heating of the electrons. This suggests that the electron beam is dissipated by quasilinear effects. Indeed, the electron beam disappears away from the step. Although we could not detect it, we suspect an ion beam to be present within the step producing large ion-acoustic fluctuations giving rise to the large anomalous resistivity. This beam is dissipated on the low side of the jump heating the ion distribution. On the low side of the jump, far away from it an ion acoustic turbulence is excited by the electron drift. The dip in plasma density within the jump is probably maintained by the ponderomotive forces of the fluctuations.

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